

Operational Earthquake Forecasting: State of Knowledge and Guidelines for Utilization

INTERNATIONAL COMMISSION ON EARTHQUAKE FORECASTING FOR CIVIL
PROTECTION

Executive Summary

I. Introduction

Under an ordinance issued by the President of the Council of Ministers of Italy in the aftermath of the L'Aquila earthquake, Dr. Guido Bertolaso, the head of the Dipartimento della Protezione Civile (DPC), appointed an International Commission on Earthquake Forecasting for Civil Protection (referred to here as the Commission) to (1) report on the current state of knowledge of short-term prediction and forecasting of tectonic earthquakes, and (2) indicate guidelines for utilization of possible forerunners of large earthquakes to drive civil protection actions, including the use of probabilistic seismic hazard analysis in the wake of a large earthquake. Appointed to the Commission were geoscientists from China, France, Germany, Greece, Italy, Japan, Russia, United Kingdom, and United States with wide experience in earthquake forecasting and prediction.

The Commission was convened in L'Aquila on May 12, 2009, and reported its findings and recommendations on October 2, 2009. During this study period, the Commission reviewed research on earthquake prediction and forecasting, drawing from developments in seismically active regions worldwide, and it received a wide array of input on the operational aspects of earthquake forecasting in Italy and elsewhere.

II. Science of Earthquake Forecasting and Prediction

This report considers both probabilistic forecasts and deterministic predictions. A *prediction* is a deterministic statement that a future earthquake will or will not occur in a particular geographic region, time window, and magnitude range. In contrast, a *forecast* gives a probability (greater than zero but less than one) that such an event will occur.

The Commission has reviewed the physical basis and observational evidence for earthquake *predictability*—the degree to which the future occurrence of earthquakes can be determined from the observable behavior of earthquake systems. The periodic rupture of geologic faults in characteristic earthquakes, which might be expected from simple versions of the elastic rebound theory, is rarely observed in nature. Many factors complicate earthquake sequences, including the complex geometries of fault branching, the chaotic nature of rupture processes, small-scale variations in the forces that act on faults to produce earthquakes, and the changes in these forces from earthquakes on other faults.

An alternative prediction strategy is to search for diagnostic precursors—signals observed before earthquakes that indicate the location, time, and magnitude of an impending event. Several types of precursors have been investigated in laboratory experiments on rock failure, but observing these precursors on the scale of tectonic earthquakes has proven to be difficult. The fault ruptures that generate earthquakes occur in highly variable geologic structures under conditions not easily replicated in the laboratory. Moreover, the eventual size of a rupture,

measured by the earthquake magnitude, depends on the processes that stop the rupture as well as those that start it.

The aim of earthquake forecasting is to quantify knowledge about future earthquake occurrence. Long-term forecasts provide probabilistic estimates of where earthquakes will occur, how large they might be, and how often they will happen, averaged over time intervals of decades. This information is essential for seismic hazard mapping, and it is the foundation on which the operational methodologies of earthquake forecasting are built.

Earthquakes tend to cluster in space and time. Large earthquakes invariably produce aftershocks by stress triggering, and sequences of earthquakes, such as those that preceded the L'Aquila earthquake of April 6, 2009, are common. Aftershock excitation and decay, as well as other aspects of earthquake clustering, show statistical regularities on time scales of hours to months that can be captured in short-term earthquake forecasts. Additional information on earthquake probabilities over the medium-term (months to years) can be obtained from the disturbance of the tectonic forces acting on faults caused by previous large earthquakes.

The Commission examined criteria that should be used to qualify earthquake forecasting methods for operational use. All operational forecasts require descriptions of their uncertainties, and the quality of a forecasting method should be evaluated for its reliability (correspondence to observations collected over many trials) and its skill (performance relative to a standard forecast). Assessing forecast quality requires prospective as well as retrospective testing against the observed seismicity. Methods for forecasting on different spatial and temporal scales should be consistent; for example, short-term forecasts based on seismic clustering should be consistent with the long-term forecasts used in seismic hazard analysis. The qualification of a forecasting method for operational purposes also depends on its value to decision-makers.

III. Status of Operational Earthquake Forecasting

The goal of operational earthquake forecasting is to provide communities with information about seismic hazards that can be used to make decisions in advance of potentially destructive earthquakes. The Commissioners from countries with areas of high seismic risk (China, Greece, Italy, Japan, Russia, United States) reported on how their national and regional agencies use operational forecasting in earthquake risk management. They also described their current procedures for the evaluation of earthquake predictions and forecasts. In most of these countries, these evaluations are done by expert panels of earthquake scientists who report directly to agency leaders.

In all of the countries, time-independent earthquake forecasting models are official products used in seismic hazard mapping. Time-dependent forecasting models have been developed for specific areas in Japan, China, and U.S. National protocols for the operational use of medium-term and short-term forecasts have not yet been established. In California, however, short-term forecasts are updated hourly based on seismicity activity, and operational procedures have been established for the utilization of short-term forecasts.

Short-term forecasting methods are under development in many regions, including Italy. After the L'Aquila earthquake of April 6, 2009, aftershock forecasts were issued on a daily basis by Istituto Nazionale di Geofisica e Vulcanologia (INGV).

IV. Key Findings and Recommendations

In adherence to its charge, the Commission has reviewed the knowledge about earthquake predictability and its current implementation in prediction and forecasting methods, and it has described in general terms the assessments of quality, consistency, and value that are needed to guide the operational utilization of such methods. This section states the Commission's key findings and makes specific recommendations regarding policies and actions that can be taken by DPC to improve earthquake forecasting and its utilization in Italy. The Commission recognizes that Italian earthquake science is already moving forward in high gear, and its recommendations are intended to help DPC and its partner organizations increase this momentum and utilize research results for the public welfare.

A. Need for Probabilistic Earthquake Forecasting

The public needs information about future earthquakes. However, earthquake generation is a very complex process occurring in an underground environment that is very difficult to observe. Given the current state of scientific knowledge, individual large earthquakes cannot be reliably predicted in future intervals of years or less. In other words, reliable and skillful deterministic earthquake prediction is not yet possible.

Any information about the future occurrence of earthquakes contains large uncertainties and, therefore, can only be evaluated and provided in terms of probabilities. Probabilistic earthquake forecasting can convey information about future earthquake occurrence on various time scales, ranging from long term (years to decades) to short term (months or less). Probabilistic forecasting is a rapidly evolving field of earthquake science.

Recommendation A: DPC should continue to track the scientific evolution of probabilistic earthquake forecasting and deploy the infrastructure and expertise needed to utilize probabilistic information for operational purposes.

B. Earthquake Monitoring

Earthquake monitoring has improved considerably since the digital revolution began several decades ago. Owing to investments in digital seismic and geodetic technology, new data on earthquake processes are accumulating rapidly. However, many of the key processes that control fault rupture are still poorly known, such as the stresses that act on faults to produce earthquakes and the slow motions that sometimes accompany (and may precede) rapid fault failures. It is very likely that further judicious investments in observational technologies and data collection programs will benefit the operational capabilities of earthquake forecasting.

Not all of the high-quality information from seismic networks run by different agencies is currently available to DPC. Strain-rate monitoring and other types of geodetic analysis are also distributed across several agencies that process the data using independent methods.

Recommendation B.1: DPC should coordinate across Italian agencies to improve the flow of data, in particular seismic and geodetic monitoring data, into operational earthquake forecasting.

Recommendation B.2: Particular emphasis should be placed on real-time processing of seismic data and the timely production of high-quality earthquake catalogs and strain-rate maps.

The determination of earthquake properties in near real time is a capability critical for short-term operational forecasting, including aftershock forecasting and forecasting during seismic swarms. Earthquake catalogs and strain-rate maps are essential products for developing long-term forecasts.

Well-instrumented ‘natural laboratories,’ such as Parkfield in the U.S. and Tokai in Japan, have provided high-quality and high-density observations of earthquake generation processes, including precursory processes, which have proven useful in testing scientific hypotheses about earthquake predictability. Natural laboratories in Italy could provide unique observations relevant to the types of earthquakes that occur in its tectonic situation.

Recommendation B.3: Opportunities for establishing well-instrumented natural laboratories for studying earthquake generation processes should be supported.

C. Research on Earthquake Predictability

Despite over a century of scientific effort, the understanding of earthquake predictability remains immature. This lack of understanding is reflected in the inability to predict large earthquakes in the deterministic short-term sense. The Commission has identified no method for the short-term prediction of large earthquakes that has been demonstrated to be both reliable and skillful.

In particular, the search for precursors that are diagnostic of an impending earthquake has not yet produced a successful short-term prediction scheme. The Commission has critically reviewed the scientific literature on phenomena proposed as diagnostic precursors, including strain-rate changes, changes in seismic wave velocities, electromagnetic signals, changes in groundwater levels and flow, radon anomalies, and acoustic emissions. In well-monitored regions, retrospective analyses of data collected prior to large earthquakes, including the L’Aquila mainshock of 6 April 2009, show no convincing evidence of diagnostic precursors.

In many cases of purported precursory behavior, the reported observational data are contradictory and unsuitable for a rigorous statistical evaluation. One related problem is a bias towards publishing positive rather than negative results, so that the rate of false negatives (earthquake but no precursory signal) cannot be ascertained. A second is the frequent lack of baseline studies that establish noise levels in the observational time series. Because the signal behavior in the absence of earthquakes is often not characterized, the rate of false positives (signal but no earthquake) is unknown. Without constraints on these error rates, the diagnostic properties of the signal cannot be evaluated.

Methods that use patterns of regional seismicity to predict large earthquakes have been the subject of considerable research. A subclass based on pattern recognition techniques are being tested prospectively, and some may show probability gain relative to long-term earthquake forecasts. However, error rates and the large areal extent of the predictions do not yet provide the diagnostic capability needed for operational predictions.

Despite this negative assessment, the search for diagnostic precursors should not be abandoned, and more fundamental research on the underlying earthquake processes is required. Current knowledge about earthquake precursors is poor, and many intriguing observations have yet to be fully explored. Among the important recent discoveries are transient deformations that propagate along some plate-boundary faults at rates much slower than ordinary seismic ruptures. Research on these phenomena will improve the understanding of earthquakes and may produce results with implications for operational earthquake forecasting.

Recommendation C: A basic research program focused on the scientific understanding of earthquakes and earthquake predictability should be part of a balanced national program to develop operational forecasting.

Although the search for diagnostic precursors should continue as a component of basic research, the Commission is not optimistic that diagnostic precursors will provide an operational basis for deterministic earthquake prediction in the near future. The best operational strategy is to accelerate the development of probabilistic earthquake forecasting.

D. Development of Long-Term Forecasting Models

The simplest, most widely-used long-term forecasting models assume earthquakes happen randomly in time, i.e. the system of seismicity has no memory. Such time-independent models are currently the most important forecasting tools for civil protection against earthquake damage, because they provide fundamental information about where earthquakes will occur, how big they can be, and how often they may happen. Such forecasts are the foundation for the seismic hazard mapping that guides earthquake safety provisions of building codes, performance-based seismic design, and other risk-reducing engineering practices, such as retrofitting to correct design flaws in older buildings. As the experience across many countries demonstrates, stringent building codes and seismic retrofitting regulations are the most effective measures communities can adopt to ensure seismic safety.

The time-independent earthquake forecast for Italy, which was published in 2004, identified the L'Aquila region to be amongst those with the highest potential for expected ground shaking. In recent earthquakes, some areas experienced ground shaking at a level that was higher than that expected, especially close to the fault and on specific sites whose geological and soil characteristics amplified the ground motion, perhaps because the current seismic hazard map of Italy does not take into account site amplification effects and near-fault wave propagation effects.

In addition, the current hazard map is based on earthquake sources distributed in seismogenic volumes, rather than on sources assigned to mapped faults. Moving towards a fault-based rupture forecast of the sort that underlies the seismic hazard models for Japan and the United States could improve the time-independent forecast. However, the tectonic complexity of Italy makes a complete enumeration of individual faults difficult. Research is underway on 'fault-system' representations that aggregate individual faults into source volumes, a plausible intermediate step.

One class of earthquake forecasts accounts for some long-term memory of past events, which makes the earthquake probability time-dependent. For example, after one earthquake on a fault segment, another earthquake on that segment may be less likely until enough time has elapsed to build sufficient stress for another rupture. Owing to Italy's tectonic complexity, this type of renewal modeling is difficult to apply and remains in the research phase. A second class of time-dependent model is based on the long-term space-time clustering of earthquakes observed in historical catalogues.

A fundamental uncertainty in long-term earthquake forecasting is the short sampling interval available from instrumental seismicity catalogs and historical records. Even though Italy has a long recorded history of earthquakes, the recurrence intervals are still highly uncertain. Field work to identify active faults, their slip rates, and recurrence times is needed.

Recommendation D: DPC should continue its directed research program on development of time-independent and time-dependent forecasting models with the objective of improving long-term seismic hazard maps that are operationally oriented.

E. Development of Short-Term Forecasting Models

On short time scales, say less than a few months, earthquake sequences show a high degree of clustering in space and time; one earthquake can trigger others. The probability of triggering increases with initial shock's magnitude and decays with elapsed time according to simple (nearly universal) scaling laws. This description of clustering explains many of the statistical features observed in seismicity catalogs, such as aftershocks, and it can be used to construct forecasts that indicate how earthquake probabilities change over the short term.

Properly applied, short-term aftershock forecasts have operational utility, because they allow civil protection authorities and the population at large to anticipate the aftershocks that inevitably follow large earthquakes. Aftershock forecasting can likely be improved by incorporating more information about main shock deformation patterns and geological settings, such as more detailed descriptions of local fault systems.

Recommendation E.1: DPC should emphasize the deployment of an operational capability for forecasting aftershocks.

The models of earthquake triggering and clustering used in aftershock forecasting can be more generally applied to short-term earthquake forecasting. Additional information from the retrospective analysis of foreshocks, earthquake swarms, and other aspects of seismicity behavior can be used to improve the estimates of short-term earthquake probabilities.

Recommendation E.2: DPC should support development of earthquake forecasting methods based on seismicity changes to quantify short-term probability variations.

F. Verification of Earthquake Forecasting Methods

Forecasting models considered for operational purposes should demonstrate reliability and skill with respect to established reference forecasts, such as long-term, time-independent models. Many proposed schemes for earthquake forecasting can be rejected as candidates for operational use because they show no significant probability gain relative to the reference forecast.

Verification of reliability and skill requires objective evaluation of how well the forecasting model corresponds to data collected after the forecast has been made (prospective testing), as well as checks against data previously recorded (retrospective testing). Experience has shown that such evaluations are most diagnostic when the testing procedures conform to rigorous standards and the prospective testing is blind. An international collaboration to establish the standards and infrastructure for the comparative testing of earthquake forecasting models is underway, and Italian scientists are participating.

Recommendation F1: Forecasting methods intended for operational use should be scientifically tested against the available data for reliability and skill, both retrospectively and prospectively. All operational models should be under continuous prospective testing.

Recommendation F2: The international infrastructure being developed to test earthquake forecasting methods prospectively should be used as a tool for verifying the forecasting models for Italy.

At present, most verification efforts are based on evaluating the correspondence of the earthquake forecasts directly with seismicity data. However, from an operational perspective, the demonstration of forecasting value may best be cast in terms of ground motions. In other words, the evaluation of earthquake forecasts is best done in conjunction with the testing of seismic hazard forecasts against observed ground motions.

G. Utilization of Earthquake Forecasts

The utilization of earthquake forecasts for risk mitigation and earthquake preparedness requires two basic components: scientific advisories expressed in terms of probabilities of threatening events, and protocols that establish how probabilities can be translated into mitigation actions and preparedness.

An effective structure for assisting decision-makers is to have an expert panel that convenes on a regular basis to engage in planning and preparation and to interpret the output of forecasting models and any other relevant information. The responsibilities of such a panel include the timely synthesis of information necessary for situation assessments during seismic crises and also in “peacetime.” It also provides a mechanism for the evaluation of ad hoc earthquake predictions.

Recommendation G1: An independent panel of experts should be created to evaluate forecasting methods and interpret their output. This panel should report directly to the head of DPC.

One of the outstanding challenges in the operational use of probabilistic forecasts is in translating them into decision-making in a low-probability environment. Most previous work on the public utility of earthquake forecasts has anticipated that they would deliver high probabilities of large earthquakes, i.e., deterministic predictions would be possible. This expectation has not been realized. Current forecasting policies need to be adapted to a low-probability environment such as in Italy. Although the value of long-term forecasts for ensuring seismic safety is fairly clear, the interpretation of short-term forecasts is problematic because earthquake probabilities may vary over orders of magnitude, but they typically remain low in an absolute sense.

To date, there is no formal approach for converting earthquake probabilities into mitigation actions. One strategy that can assist decision-making is the setting of earthquake probability thresholds for mitigation actions. These thresholds should be supported by objective analysis, for instance by cost/benefit analysis, in order to justify actions taken in a decision-making process.

Recommendation G2: Quantitative and transparent protocols should be established for decision-making that include mitigation actions with different impacts that would be implemented if certain thresholds in earthquake probability are exceeded.

H. Public Communication of Earthquake Information

Providing probabilistic forecasts to the public in a coordinated way is an important operational capability. Good information keeps the population aware of the current state of

hazard, decreases the impact of ungrounded information and contributes to reducing risk and improving preparedness. Using web-based technology, probabilistic earthquake forecasts can be made available to the public on a continuous basis, not only during crises, but also at times when the probability of having a major event is low. This would educate people about seismicity variations, enhance the effectiveness of public communication in case of an extreme event, reduce unjustified criticism, and have a positive influence on public willingness to participate in civil protection system. Experience from various earthquake prone areas has shown that direct information through official websites accessible to the public, as well as special TV programs, are effective and well accepted ways to communicate. The principles of effective public communication have been established by social science research and should be applied in communicating seismic hazard information.

Recommendation H: DPC, in accordance with social-science principles on effective public communication and in concert with partner organizations, should continuously inform the public about the seismic situation in Italy based on probabilistic forecasting.

I. Roadmap for Implementation

The Commission has identified several interrelated activities that could improve the scientific basis for, and the reliability of, operational earthquake forecasting. This section summarizes the actions that arise from our main conclusions in order to utilize forecasting techniques currently being investigated to drive civil protection actions.

The development of any new operational protocol requires progress in three phases. First is a research phase, where information is collated and forecasting models are constructed. This should be followed by a testbed phase, where forecast models are compared in terms of their quality and consistency, followed by an implementation phase that includes verification of forecast value that can be used in turn to define thresholds for civil protection actions. Clearly any practical use of forecasting methods must be done in an appropriate policy framework, one that can weigh costs against benefits and potential gains against possible risks. The following actions are under way or have been initiated by DPC and the relevant Italian agencies.

1. Underway

- Encourage basic research on earthquakes and their predictability.
- Continue a directed research program on the development of long-term seismic hazard maps in order to provide a basic reference model against which others may be judged for predictive power.
- Develop the capability to integrate seismic and geodetic data streams collected by different agencies to provide a real-time processing infrastructure, so that basic data and information derived from it can be provided consistently and quickly.
- Gain experience from the exercise of forecasting aftershocks as the best current example of a relatively skilled, low-probability forecast, and anticipate the potential use of other forms of forecasting based on observation of earthquake clustering.
- Encourage the relevant agencies to participate in global testing programs to quantify reliability and skill in earthquake forecasting with current knowledge.
- Continuously inform the public by providing accessible, appropriate and timely information on the current status of earthquake hazard based on probabilistic forecasting.

2. Outstanding actions

The Commission has established that the science of forecasting has progressed to the stage where probability gains above background can be made, albeit in a low-probability environment. A variety of forecasting models have been proposed that quantify the probability, and a global effort is currently under way to establish the reliability and skill of such models. We recommend anticipating the emergence of such scientifically-tested forecasting models by the following actions.

- Convene a scientific advisory structure reporting to the head of DPC to provide expert advice and updates at regular intervals and rapidly at times of crisis.
- Determine how scientific results on forecasting capability may be provided to decision-makers in a useful way. This could be done by a working group, with representation of the relevant agencies, and social scientists as well as seismologists, reporting to the scientific advisory structure.
- Deploy an appropriate infrastructure to utilize low-probability forecasting for operational purposes.

Implementation must be orchestrated in a way that reduces the vulnerability of communities and improves community resilience. The legitimate and responsible scientific examination of the degree of predictability of earthquake populations is no substitute for civil protection actions well in advance of earthquakes, for example in the design and planning of new buildings, or retrofitting of older ones identified as being at risk.

V. Members of the Commission

Thomas H. Jordan, Chair of the Commission
Director of the Southern California Earthquake Centre
Professor of Earth Sciences, University of Southern California, Los Angeles, USA

Yun-Tai Chen
Professor and Honorary Director, Institute of Geophysics
China Earthquake Administration, Beijing, China

Paolo Gasparini, Secretary of the Commission
Professor of Geophysics, University of Napoli “Federico II”, Napoli, Italy
President of the AMRA (Analisi e Monitoraggio del Rischio Ambientale) Scarl,

Raul Madariaga
Professor at Department of Earth, Oceans and Atmosphere
Ecole Normale Supérieure, Paris, France

Ian Main
Professor of Seismology and Rock Physics
University of Edinburgh, United Kingdom
Co-Director of the Edinburgh Collaborative of Subsurface Science and Engineering

Warner Marzocchi
Chief scientist, Istituto Nazionale di Geofisica e Vulcanologia
Rome, Italy

Gerassimos Papadopoulos
Research Director, Institute of Geodynamics
National Observatory of Athens, Athens, Greece

Gennady Sobolev
Professor and Head Seismological Department, Institute of Physics of the Earth
Russian Academy of Sciences, Moscow, Russia

Koshun Yamaoka
Professor and Director
Research Center for Seismology, Volcanology and Disaster Mitigation
Graduate School of Environmental Studies, Nagoya University, Nagoya, Japan

Jochen Zschau
Director Department of Physics of the Earth
Helmholtz Center, GFZ, German Research Centers for Geosciences, Potsdam, Germany